Ecological Indicators 90 (2018) 438–450

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Original Articles

What drives the vegetation restoration in Yangtze River basin, China: Climate change or anthropogenic factors?

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ARTICLE INFO

Keywords:
Vegetation restoration
Climate change
Ecological engineering
Population density
Yangtze River basin

ABSTRACT

Knowledge of the vegetation dynamics is critical for addressing the potential challenges and threats facing the land surface ecosystems. Various climatic and anthropogenic factors such as temperature, precipitation, ecological engineering, and population density can affect the vegetation conditions. Yet how vegetation in the Yangtze River basin (YRB) responses to climate change and human activities is not well established. We investigate the spatiotemporal variations of vegetation coverage using Normal Difference Vegetation Index (NDVI) during 1982–2015, and distinguish the effects of climatic and anthropogenic factors on vegetation dynamics. The results show that the growing-season NDVI (GSN) has increased by 0.09% during the 34-year period, the changes indicated a significant upward trend of vegetation with annual change rates of 0.09% GSN year^{-1} during 1982–2015.especially after 1994, the vegetation coverage has significantly increased. Temperature is a controlling factor determining the vegetation greenness in YRB, and the response of vegetation to precipitation is relatively lower because of the abundant water. Meanwhile, land use changes caused by ecological restoration project is the major driving factor for improving vegetation conditions in YRB, and the spatial distributions between human-induced GSN increasing trends and areas with increased forest have a strong consistency in the north of YRB. High effectiveness of ecological restoration projects are closely related to the combined effects of topography, climate and human management. The areas in northern part of Hubei and Sichuan are characterized by suitable climate and moderate elevation, leading to a high effectiveness for vegetation restoration. For the Hengduan Mountain area with complex terrain and lower precipitation added with poor traffic accessibility, low or even no effectiveness of project implementations can be observed. Furthermore, the large-scale migration and movement of the labor force in YRB relieve the environmental pressures and improve the vegetation conditions for the region of emigration.

1. Introduction

Vegetation dynamics have been considered essential in global changes of terrestrial ecosystems (Arora, 2008; Eugster et al., 2010; Walther et al., 2002). As the link between the land and atmosphere, vegetation plays an important role in mirroring and characterizing the Earth's surface energy exchange, carbon cycle, soil ecosystems and regional human activities (Tong et al., 2016; Suzuki et al., 2007). Vegetation dynamics is a complex and long process, and it is influenced by many factors such as climatic change, land-use change, ecological engineering, and urbanization in different regions (Yu and Hu, 2013; Piao et al., 2003; Wu et al., 2014; Yao et al., 2017). Satellite imagery is one of the important data sources to monitor large-scale vegetation dynamics, which has become a widely used tool in the field of ecological protection and global climate change (Nemani et al., 2003; Pettorelli et al., 2005). The satellite-based normalized difference vegetation index (NDVI), based on the reflectance difference of red and near-infrared spectrum, has been considered to be effective in sensing trends in green vegetation and detecting inter-annual variation of vegetation coverage at regional, continental and global scales. (Pinzon and Tucker, 2014; Tüshaus et al., 2014; Guo and Lei, 2013). Recently, many studies reveal that vegetation activities have increased in the northern mid–high latitudes and the vegetation growing season has prolonged, and found that vegetation stability is changing with the external environment (Myneni et al., 1997; Zhou et al., 2009). In the context of global warming and sustainable development, the study of vegetation dynamic and its driving factors is emerging as a research focus worldwide.

Concerning the relationship between vegetation growth and climate variables, it has been detected that NDVI showed dramatic spatial variations in response to climate changes (Gong and Shi, 2003).

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https://doi.org/10.1016/j.ecolind.2018.03.029
Received 9 October 2017; Received in revised form 6 February 2018; Accepted 12 March 2018
Available online 21 March 2018
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Temperature has a marked positive influence on vegetation coverage in China, which has been the restrictive factor for vegetation growth throughout the whole country (Song and Ma, 2011; Yu and Hu, 2013). However, the relationship between precipitation and vegetation growth is characterized by the geographical heterogeneity. Vegetation coverage is positively correlated with precipitation in most dry areas whereas in humid areas, there was a negative correlation between vegetation conditions and heavy rainfall (Wang et al., 2010; Xu et al., 2014).

In addition to climate change, human activity is another key factor influencing the growth of vegetation. Along with rapid urbanization and population growth, the land use types have undergone great changes, a series of ecological problems occurred, including desertification, soil erosion, and land degradation in arid areas of Northern China (Liu and Diamond, 2005; Zhang et al., 2016). Furthermore, the impact of major Water Conservancy Projects on vegetation coverage should not be neglected, for example, the impoundment of the Three Gorges Project resulted in the expansion of non-vegetation coverage in the upper reaches, and the reconstruction of towns in the reservoir area led to the reduction of forest land and grassland (Han et al., 2013; Wang et al., 2008). In the context of global sustainable development strategy, the Chinese government has invested heavily in human resources and financial resources to improve the vegetation coverage and ecosystem conditions. Especially since the middle of 1990s, a string of large-scale ecological restoration programs such as Grain for Green Project and Yangtze River Basin Shelterbelt Construction Project have been launched, covering 25 provinces in central and southern China (Huang et al., 2013; Jia et al., 2014; Tian et al., 2015a,b). Meanwhile, with the forestation of sloping land and degraded farmland, a large number of rural labor forces have become superfluous in local demand, and the migration of labor to big cities has occurred. In areas with fragile ecological environment, the implementation of the eco-immigration program also has a profound effect on the ecological restoration (Wang et al., 2015). These kinds of movement have broken the original population structure, which in turn have affected the vegetation dynamics (Gesest et al., 2010).

Studies have found a significant increase in vegetation coverage in most parts of China using long-term NDVI data. However, most research concerning vegetation growth have focused on the combined effects of climate change and human activity on inter-annual NDVI trends (Cao et al., 2006; Evans and Geerken, 2004; Zhang et al., 2014), and the influences of human activities on vegetation coverage remain blurry and have not been discussed precisely. Despite great efforts have been made to investigate the responses of vegetation variations to climatic change, limited effort has targeted separating the effects of human-induced factors and climate variations on vegetation conditions. In addition, time-series analysis based on short periods often fails to meet the requirements of dynamic changes of vegetation coverage before and after the implementation of the afforestation project and population migration.

In order to separate the impacts between human activities and climate on vegetation dynamic, we will use long-term Earth observation (EO) data-sets to establish a NDVI-climate model, detect the residuals between observed and predicted values of vegetation trends (Evans and Geerken, 2004; Li et al., 2012; Wessels et al., 2007). Many researchers have recognized that it is unreasonable to use full time series data to develop NDVI-climate models without taking into account existing human impacts (Horion et al., 2016). Here, we introduce a turning point, and establish the model in a reference period with little artificial interference to predict a period of vegetation that should be strongly influenced by human activities (especially afforestation projects and population migration) (Cao et al., 2006; Tong et al., 2017).

YRB plays an important role in maintaining the ecological balance and security of the adjacent area and even the whole country, China. Due to the implementation of ecological engineering, population migration and climate change, the YRB has undergone major changes in environment and landscape. This study centered on vegetation dynamics and its responses to climatic variables and human activities (especially afforestation and population migration) in the YRB. The growing-season NDVI (GSN) was selected as an effective indicator for monitoring vegetation conditions (Fensholt and Proud, 2012; Tian et al., 2015a,b).

The purposes of this study are: (1) to examine the vegetation dynamics and their relationships with climatic factors in YRB, (2) to separate the influences of climate change and human-induced factors on vegetation variations, (3) to relate the human-induced vegetation trends to the ecological restoration programs and population dynamics. Our results will contribute to a better understanding of the variation characteristics and vegetation patterns under the impacts of climate change and human activities, and promote the implementation and management of ecological reconstruction programs.

2. Data and materials

2.1. Study area

The YRB (24°30′–35°45′N and 90°33′–122°25′E) originates from the east of Qinghai-Tibet Plateau, traverses three economic zones in eastern, central and western of China, and crosses 19 provinces of the whole country (Fig. 1). It covers an area of approximately

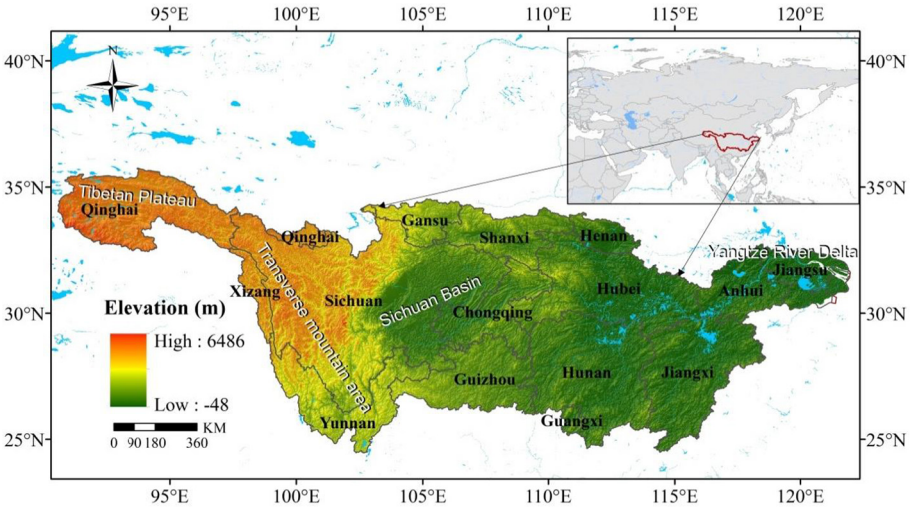

Fig. 1. Topographical map of the Yangtze River basin.

1.8×10^6 km^2, accounting for 18.8% of China's land area. The topography of the region has a declining slope from the west to the east, which has high landscape heterogeneity from Northwest of Tibet Plateau (over 4000 m a.s.l.) to lowland area such as the Yangtze River Delta Plain (below 50 m a.s.l.). The annual average temperature ranges from 12.6 to 28.0 °C and annual average precipitation is about 476 mm. The region is rich in forest resources and varieties of vegetation, occupying over 25% of the country's forest resources. There has been a significant land cover change, especially the reforestation and afforestation due to the implementation of many ecological projects and the conversion of farmland to urban land in lower reaches as a result of the aggregation of population and industry (Zhang et al., 2014). Because of relatively suitable precipitation and temperature conditions, vegetation productivity is generally high in YRB. However, human-induced factors are now having a great influence on vegetation growth (Yao et al., 2017; Zhang et al., 2014b).

2.2. Data used

The datasets used in this study consist of NDVI data, gridded temperature and rainfall data, land use/land cover data and population data. This study used the GIMMS NDVI 3 g dataset developed by the NASA Global Inventory Modeling and Mapping Studies group, with 15-day temporal resolution and 8 km spatial resolution (Tong et al., 2017). The data set covering the period from 1982 to 2015 is valuable for assessing long-term vegetation activities. To minimize the effect of cloud contamination and atmospheric variability, we calculated a monthly NDVI by using maximum value composite (MVC) of the fortnightly data set. Then the average values from March to October were obtained as the growing-season NDVI for each year from 1982 to 2015.

Climate datasets include daily temperature and rainfall data for 180 meteorological stations in YRB from 1982 to 2015 were acquired from the Chinese Meteorological Science Data Sharing Service Network (http://cdc.cma.gov.cn/home.do). The Kriging interpolation method was adopted to get the annual average temperature and rainfall data in the whole study area with a spatial resolution of 8 km to match NDVI datasets (Wang et al., 2001; Li et al., 2012).

Annual land use data from 2001 to 2013 was obtained from the refined MODIS land cover product (MCD12Q1, v51) (https://ladsweb.modaps.eosdis.nasa.gov/). Using the classification system of the International Geosphere-Biosphere Programme, we extracted five land cover types: forestland, shrubland, grassland, cropland, and non-vegetation. Forestland consists of five types: evergreen needleleaf forest (ENF), evergreen broadleaf forest (EBF), deciduous needleleaf forest (DNF), deciduous broadleaf forest (DBF), and mixed forest (MF). Forestland consists of five types: evergreen needleleaf forest (ENF), evergreen broadleaf forest (EBF), deciduous needleleaf forest (DNF), deciduous broadleaf forest (DBF), and mixed forest (MF) (Zhang et al., 2014; Zhang et al., 2014). National population space distribution kilometer grid data set from 1995 to 2010 is provided by Data Center for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn), which was created based on the census data of the whole country. Using an approach of spatial interpolation, the dataset was aggregated to 1 × 1 km resolution and the value in each grid represents the population of the square kilometer. Both land use and population spatial distribution data were resampled and transformed to the same coordinate system to match the corresponding NDVI data.

3. Methods

3.1. Linear regression analysis

In this research, a linear regression analysis method was applied to analyze the spatial and temporal fluctuations of the annual GSN. The slope (a) of the regression indicates the direction and magnitude of the temporal change: positive slopes ($a > 0$) and negative slopes ($a < 0$). By overlaying the layers of slopes and significance (p-value), the trends of GSN were categorized into three types: increase ($a > 0$, $p < 0.05$), decrease ($a < 0$, $p < 0.05$) and stable (no significant trend at 5% level).

Correlation coefficients between the mean annual NDVI (dependent variable) and annual average precipitation and temperature (independent variables) in the growing season were estimated using an ordinary least-squares regression method. Then significance of the correlation coefficients between GSN and climatic factors at the 95% level were analyzed.

3.2. Mann-Kendall test

In this study, we adopt the Sequential version of Mann-Kendall test statistic to identify the potential turning point in the time series of the annual GSN trend (Mohsin and Gough, 2010; Safari, 2012). The application of which has the following steps in sequence: $x_i = x_1, x_2 \ldots, x_n$ are replaced by their ranks y_i in ascending order. Comparing each y_i magnitudes with y_i, (j = 1, 2, 3, i−1), the cases $y_i - y_j$ are counted and denoted by n_i. A statistic t_i can be defined as follows:

$$t_i = \sum_{j=1}^{i} n_i \tag{1}$$

The test statistic distribution s t_i, has a mean as

$$E(t_i) \frac{i(i-1)^2}{4} \tag{2}$$

and a variance as

$$\mathrm{Var}(t_i) \frac{i(i-1)(2i+5)}{72} \tag{3}$$

The sequential values of the standardized variable $u(t_i)$ are calculated as:

$$u(t_i) = \frac{[t_i - E(t_i)]}{\sqrt{\mathrm{var}(t_i)}} \tag{4}$$

$$u'(t_i) = -u(t_i) \tag{5}$$

Here, $u(t_i)$ is a forward sequential statistic which is estimated using the original time series. Similarly, the values of $u'(t_i)$ can be computed backward starting from the end of the series. The intersection of the two statistical curves represents the potential turning point (Chatterjee et al., 2014; Tong et al., 2017). Then the significance was examined at the 95% level ($p < 0.05$).

Considering the intensive human activities i.e., large-scale ecological afforestation and population migration, in the YRB in recent years, we speculated that the turning point was mainly caused by anthropogenic factors. The year of turning point separated the time series into two periods. The vegetation in the first (reference) period (1982–1994) was characterized as a baseline where vegetation was not strongly affected by human-induced factors, and the second (conservation) period (1995–2015) was characterized as the impact of human activities relative to the first period (Wang et al., 2015).

3.3. Residuals analysis

Residual analysis method was utilized to separate human induced vegetation trends from those of climate (Fig. 2). This method takes a pixel-based approach to identify the dominant driver of vegetation dynamics by calculating the residuals between observed NDVI and predicted NDVI values (He et al., 2015; Li et al., 2012). We used the first (reference) period to establish a multiple regression models between NDVI (dependent variable) and climatic variables (precipitation and temperature as independent variables) based on monthly observations. The NDVI-climate regression model for the first (reference)

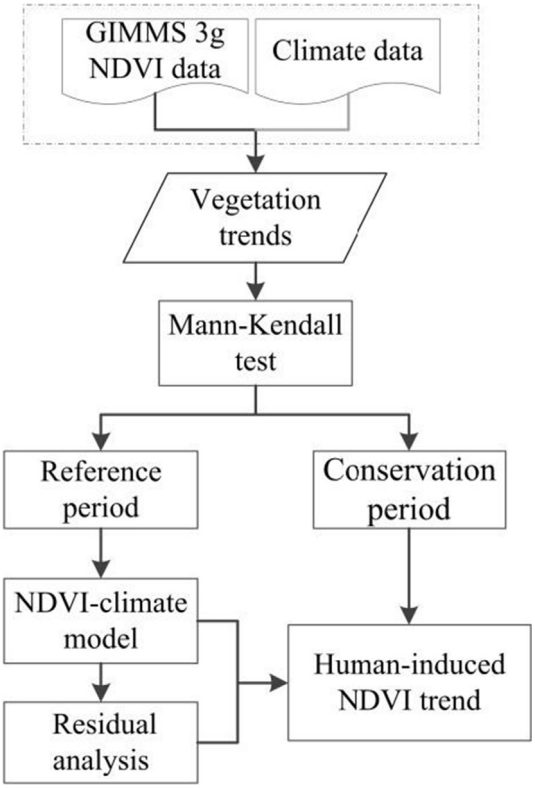

Fig. 2. Working procedure for separating climate from human induced vegetation trends.

period is shown in the following equation:

$$\mathrm{NDVI}(i,m) = \mathrm{A}*\mathrm{T(i,m)} + \mathrm{B}*\mathrm{P(i,m)} + \mathrm{C} \quad (6)$$

where i indicates the location of the pixel, m is the month, A, B are the regression coefficients of NDVI and temperature (T) and precipitation (P) of m month, respectively, C is a constant. Only regions where NDVI and climate were significantly associated (95% level) were kept and the regression coefficients were used to calculate predicted GSN for the conservation period (which is assumed to be climate driven only). Then the residuals can be calculated by the difference between the observed GSN and the predicted GSN for the conservation period, which reflected the effects of human activities in the vegetation trends (Wang et al., 2015; Tong et al., 2017). Based on the linear regression method, the influences of human-induced on vegetation changes were obtained. If the residuals show no trend over time, the observed changes in vegetation are considered to be affected by climatic factors, a decreasing trend indicates that human activities have a negative impact on vegetation cover changes and an increasing trend describes that human activities (afforestation and population migration are assumed) have contributed to vegetation growth.

It is noteworthy that the residual analysis method is only applicable to areas with significant correlations between NDVI and climatic factors. For those areas where in the first period NDVI changed significantly and NDVI-climatic control is not significantly correlated, the influence of anthropogenic factors on vegetation changes exceeded the climatic factors, underlying that climatic drivers have little effect on vegetation in these pixels. Then we get the influence of human activities by intersecting with the significant changes of GSN (Huang et al., 2012).

3.4. Ecological afforestation project analysis

A spatial superposition analysis is employed to analyze the effectiveness of the ecological afforestation projects, and layers of land cover conversions and vegetation coverage trends are integrated (Li et al., 2016; Li et al., 2012). Due to their weak relationship with the ecological afforestation project, the areas of the land types of water bodies, farmland and urban land in 2013 were classified as no significant effectiveness and the situation are same as the areas where land use types have not changed since 2001. Then for the regions where other vegetation types such as farmland and grassland are converted to forestland, if there is a significant correlation between NDVI and climate (95% level), the residual NDVI time-series determined if the pixel vegetation coverage had increased with time, suggesting a high effectiveness afforestation restoration, or vice versa for moderate and low effectiveness. While for regions with increased woodland and no significant correlation between NDVI and climate, only GSN temporal trends were examined to evaluate the effectiveness (Huang et al., 2012).

3.5. Spearman correlation analysis

To investigate the correlations between the change tendency of vegetation and the population density factors (average population density and change values), the spearman correlation analysis based on their rank orders was adopt to provide robust insights into their relationship. In consideration of the nonlinear relationship and interaction between vegetation trends and population density variables, the spearman coefficient method avoided any non-linearity that could obstruct the detection of a monotonic correlation.

4. Results

4.1. Vegetation trends and the turning point

By analyzing the trend of annual average GSN, the changes indicated a significant upward trend of vegetation with annual change rates of 0.09% GSN year^{-1} during 1982–2015 ($p = 0.001$) (Fig. 3b). Peaks of GSN trend occurred 1990 and 2009, and troughs were mainly observed in 1994 and 2000. The occurrence of extreme values is partly related to extreme weather events (Wang et al., 2015). Mann-Kendall test statistics detected that the forward trend of annual GSN intersected the backward trend in the year 1994, which was suggested as a turning point. The GSN trend fluctuated considerably before 1994 and tended to grow steadily positive after this year (Fig. 3a). In view of this turning point, we found a gentle downward trend for the first (reference) period (1982–1994) and a weak significant increasing trend for the second (conservation) period (1995–2015) (Fig. 3b). In the conservation period, the overall value of GSN is much higher than the reference period.

Vegetation changes in YRB exhibited spatial heterogeneity. The spatial distribution of mean annual GSN is related to land cover types, and the areas with high GSN value are mainly forest land (Fig. 4). The highest GSN values (0.86) occurred in areas dominated by deciduous broadleaf forests and mixed forests in the north of Jiangxi Province, and low GSN values were mainly involved in farmland, urban/built up land, barren, and other areas with lower vegetation coverage found mainly in the western part of the YRB, as well as in the eastern and central industries and population agglomeration areas.

Based on a linear regression analysis method, over the past 30 years, the annual GSN in more than 71% of the region showed an increase trend, and of which over 31% showed a significant uptrend. The largest trends (more than 2.6% GSN year^{-1}) occurred mostly concentrated in the central region of YRB (Fig. 5a), especially in the northeastern part of Sichuan Province and the middle of Chongqing. The decreasing trend accounted 28% of the whole region, and among which about 5% showed a significant downtrend. However, the significant decreasing trends were relatively dispersed, mostly distributed in the Suzhou and Shanghai areas of the Yangtze River Delta, and thus, vegetation changes in YRB exhibit obvious regional characteristics.

Vegetation trends varied considerably between the reference and conservation period periods (Fig. 5b, c). During the reference period,

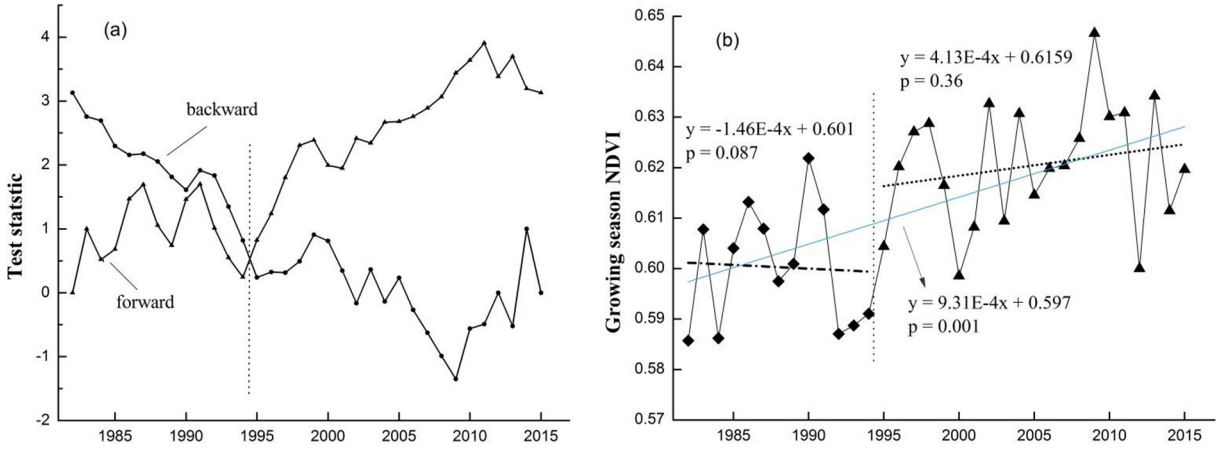

Fig. 3. (a) Abrupt changes in annual GSN based on Mann-Kendall test. The intersection is the year in which turning point in the mutation took place. (b) The inter-annual variations and linear trends of GSN for the whole period; the two stages before and after the turning point (1982–1994 and 1995–2015).

47.6% of the YRB showed an increasing trend, and the area with significant vegetation improvements (primarily in the Zhidoi and Qumarlêb counties of Qinghai province) accounted for 4% of the total. 52.4% of the area suffered a certain degree of vegetation degradation, with a significant decreasing in vegetation of 1%, mainly distributed in the rapid development of urbanization in Chengdu and Yibin cities of Sichuan province. However, in the conservation period, 58.6% of the study area has experienced an increase in GSN, among which 12.1% of the study area showed a significant uptrend (mostly concentrated in the east of Sichuan Province and south of Shaanxi province). Meanwhile, decreasing trends were found in the Hengduan Mountains in the west of Sichuan province, accounting for 41.4% of the study area, and of which over 8.8% showed a significant downtrend. The difference of slope in these two periods also showed obvious spatial variation (Fig. 5d). Comparing with the reference period, 48% of the study area had a greater GSN slope during the conservation period. At the same time, the largest slope difference (more than 0.03 GSN year^{-1}) of vegetation change in the two periods was mainly distributed in the southwest of Sichuan province and northwest of Guizhou province. The GSN slopes in the second period (1995–2015) lower than the first period (1982–1994) were mainly located in the western part of Sichuan and Yunnan province as well as in most of Shanghai city. The main reason for the decreasing vegetation coverage in these areas is urbanization and the large-scale rural population to urban agglomeration, resulting in encroachment and destruction of vegetation (Barbieri and Carr, 2005).

4.2. The relationship between GSN and climate change

In the past 30 years, the correlation between GSN and temperature is gradually changed from negative in the west to positive in the east (Fig. 6a). In 76.8% of the area, GSN was positively correlated with temperature, the area with p values < 0.05 accounted for 34.1% of the total area, mainly in the eastern part of Hunan province and most of Jiangxi province. These areas have a humid climate and sufficient rainfall to meet the needs of shrubs and mixed wood-based vegetation, so the rise in temperature has a positive effect on vegetation growth. However, in the southwestern region of Guizhou Province and Yunnan Province, the widely distributed karst landform lacks the precipitation, and the negative effects of soil moisture deficit caused by rising temperature outweighed the positive effects of growing season extension. Higher temperature will enhance the evapotranspiration and thus reduce the vegetation coverage (Guo and Lei, 2013; Zhang et al., 2015). In Sichuan Province, however, persistent droughts and frequent forest fires (over 4500 times between 1982 and 1999) in summer may be the main cause of GSN reduction (LI et al., 2013; Hua et al., 2017). Regions where the correlation coefficients during the conservation period (1995–2015) exceeded the reference period (1982–1994) mainly distributed in Hubei Province (Fig. 6c and d). Whereas areas in which the correlation coefficients during the conservation period were lower than the reference period were mainly distributed in the southern regions of Hunan Province and Guizhou province. The main reason is that the areas of woody savanna and the savanna have been transformed into farmland and mixed vegetation (Wang et al., 2015).

The correlation coefficients between precipitation and GSN in most parts of YRB (60.8%) from 1982 to 2015 have been dominated by

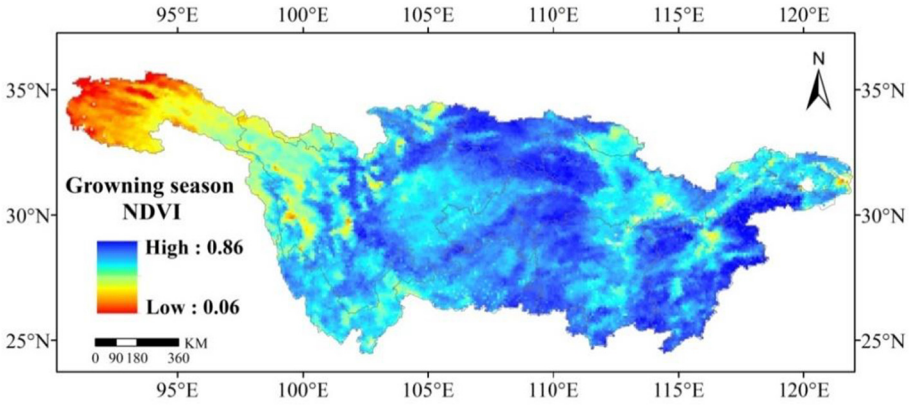

Fig. 4. Spatial distribution annual mean GSN in YRB from 1982-2015.

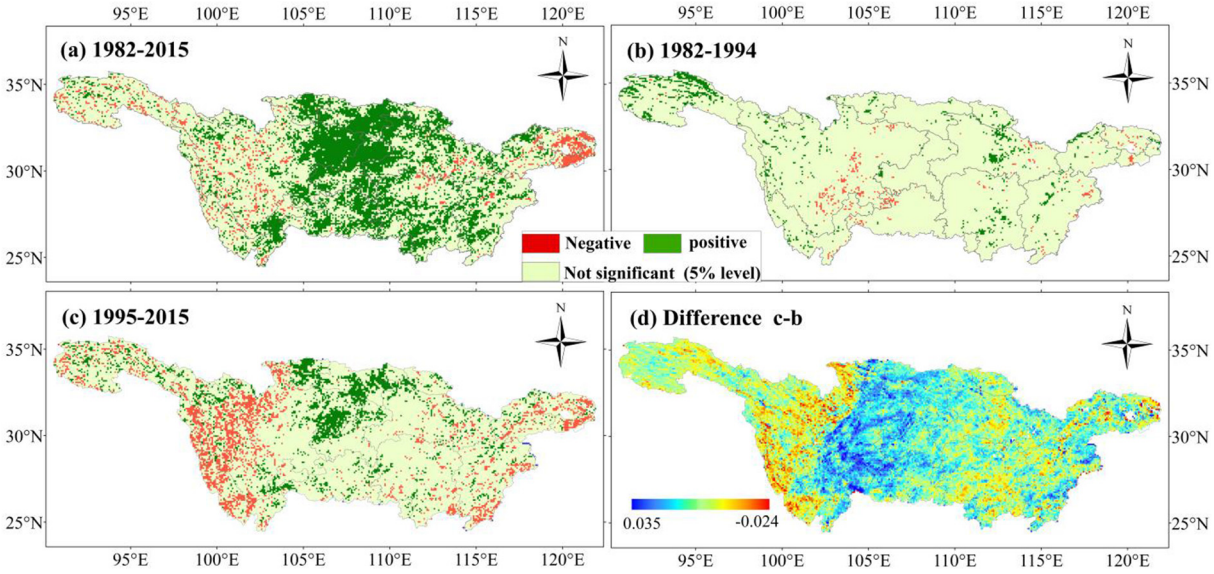

Fig. 5. Change trends of the mean GSN for different periods (a) 1982–2015; (b) 1982–1994; (c) 1995–2015; and (d) the differences in vegetation trends between reference (1982–1994) and conservation (1995–2015) periods.

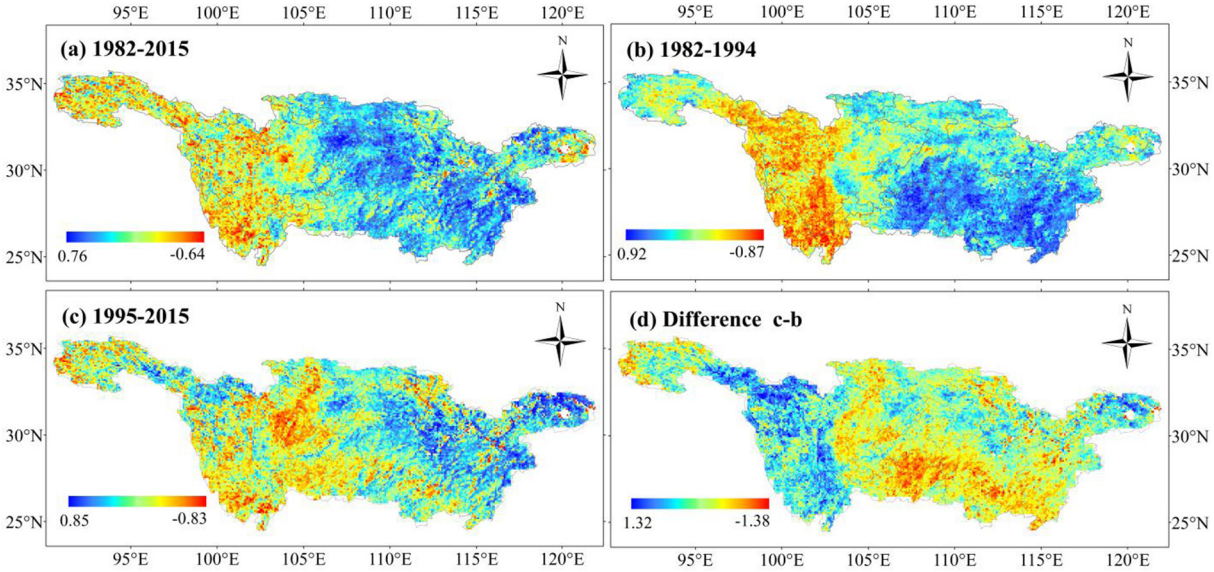

Fig. 6. Spatial pattern of the correlation coefficients between GSN and temperature for different periods. (a) 1982–2015; (b) 1982–1994; (c) 1995–2015; (d) the differences in correlation coefficients between reference (1982–1994) and conservation (1995–2015) periods.

negative correlation (Fig. 7a). The reason for this result is that abundant water system reduces the dependence of the vegetation on precipitation. At the same time, excessive precipitation will aggravate soil erosion and flooding, destroying the vegetation environment. Only 39.2% of the study area had a positive correlation coefficient between precipitation and GSN, among which 1.4% of pixels had p values of < 0.05, mainly distributed in the western and northeastern Yunnan province. Due to arid and hot geographical environment, the increase of precipitation under the influence of Southwest monsoon could reduce the restriction of water on vegetation growth in these areas. Compared with the reference period, regions with lower correlation coefficients during the conservation period mainly located in the southwestern part of Sichuan Province, as deforestation and urbanization in these areas have destroyed vegetation. The increased correlation between GSN and precipitation was mainly distributed in the eastern part of Sichuan Province and Chongqing city, (Fig. 7b–d). The reason is that the vegetation type has changed from farmland to woodland because of the effect of Grain for Green Project (Tong et al., 2017).

4.3. Trends of residual analysis

The variation in residual trends could reflect the intensity of human activities on vegetation coverage, and majority (54.31%) of the pixels with significant ($p < 0.05$) correlation between NDVI and climate variables are taken. Mean residual slopes in YRB were detected between −0.015 and 0.034, and 47.37% of the study area showed a positive trend mainly in the southern part of Shaanxi province and eastern Sichuan province (Fig. 8). The vegetation greening up in these areas has been largely exceeded the climate-only explanation, suggesting that improvements in vegetation conditions may be due to afforestation and ecological projects as well as population migration (positive impact). The areas with negative trends (52.63%) were mainly located in the west and south of Sichuan province, as well as in the east of Shanghai. Here, vegetation growth was lower than climate change expectations, indicating that human activities may lead to vegetation degradation (negative impact). After the statistic test, the vegetation coverage in 9.02% of the area was significantly increased due to human activities,

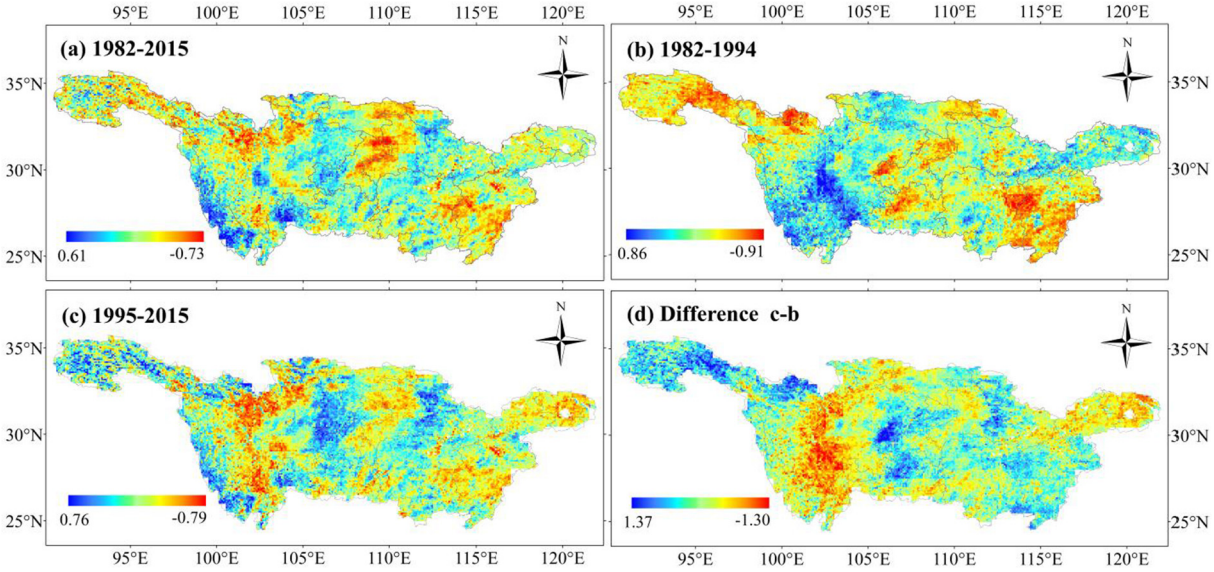

Fig. 7. Spatial pattern of the correlation coefficients between GSN and precipitation for different periods (a) 1982–2015; (b) 1982–1994; (c) 1995–2015; and (d) the differences in correlation coefficients between reference (1982–1994) and conservation (1995–2015) periods.

and the vegetation coverage in 9.89% of the area was degraded by human activities.

4.4. Relationship between human-induced GSN trends and the implementation of ecological projects

4.4.1. Land use change and NDVI superposition analysis

The annual land use data derived from MCD12Q1 showed that the land use structures have changed dramatically in YRB over the last 13 years (Fig. 9). Two major types of land use conversion have taken place: from shrub and grass to forest, as well as from farmland to shrub and forest. A significant increase occurred in forest area, with a growth of $2.83 \times 10^5\,km^2$ from 2001 to 2013, which accounting for 15.86% of the basin (Fig. 9c, Table 1). The areas of forest coverage growth were mainly located in the northeastern part of Sichuan Province and western part of Hubei Province. 3.18% of the areas with declining forest land are located in the Hengduan Mountains in the southwest of China. Since the implementation of the policy of Grain to Green Program, there has been a slow decline ($-0.33\%\,yr^{-1}$, $p < 0.05$) in farmland from 2002 to 2013 (Fig. 9d). Farmland converted to shrub and forest area of 5.15×10^4 and $2.69 \times 10^4\,km^2$, accounting for farmland transferred to other land types of 30.19% and 57.92%, respectively. The regions were mainly distributed around the Sichuan basin and the northern part of Guizhou Province. The grassland area showed a gradual downward trend ($-0.18\%\,yr^{-1}$, $p < 0.01$), of which $2.71 \times 10^5$and $3.52 \times 10^5\,km^2$ are now shrub and forest land, respectively (Fig. 9d, Table 1).

The results of the superposition analysis showed that the change of vegetation conditions was associated with the conversion of land use types (Fig. 10a, b). There are four types of land conversion in the area of vegetation coverage growth: farmland to shrub, farmland to forest, other land use types to shrub, and other land use types to forest. The obvious geographical variations occurred in YRB were the transitions from farmland to shrub in the central of study area (concentrated in the northern part of Sichuan province and the western regions of Guizhou province) and farmland to forestland mainly distributed in the eastern part of Sichuan Province and the western part of Hubei Province (Fig. 10a). The newly-added forestland was widely distributed, in which Chongqing, Hubei and Hunan province was relatively concentrated. In vegetation degraded areas, the transition from forestland and shrub to grassland was the main type of land use conversion, which accounted for 8.17% of the changed degraded land. The conversion of forestland and farmland to urban land occupied a smaller proportion in the degraded area, which was 5.07%, mainly distributed in the Yangtze River Delta and the southwest of Henan Province (Fig. 10b).

4.4.2. Effectiveness of ecological restoration projects

Based on the analysis of GSN and land use changes, we determined the effectiveness of the implementation of ecological afforestation projects in YRB at the pixel scale (Fig. 10c). The area of woodland

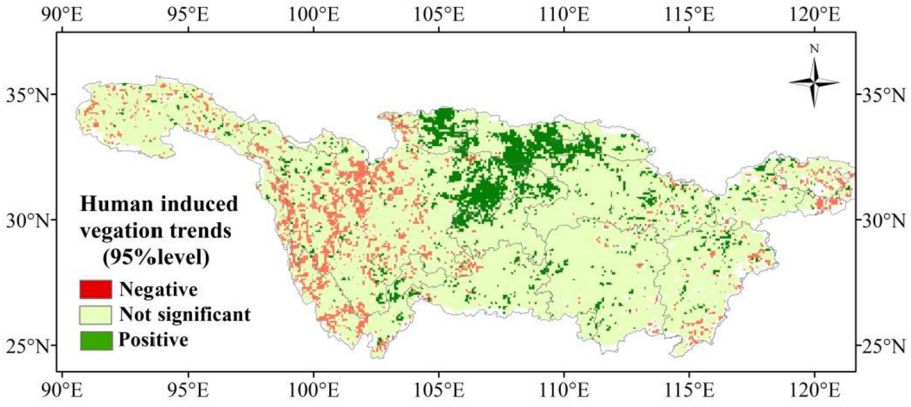

Fig. 8. Human induced vegetation trends: positive, negative, and no significant trend.

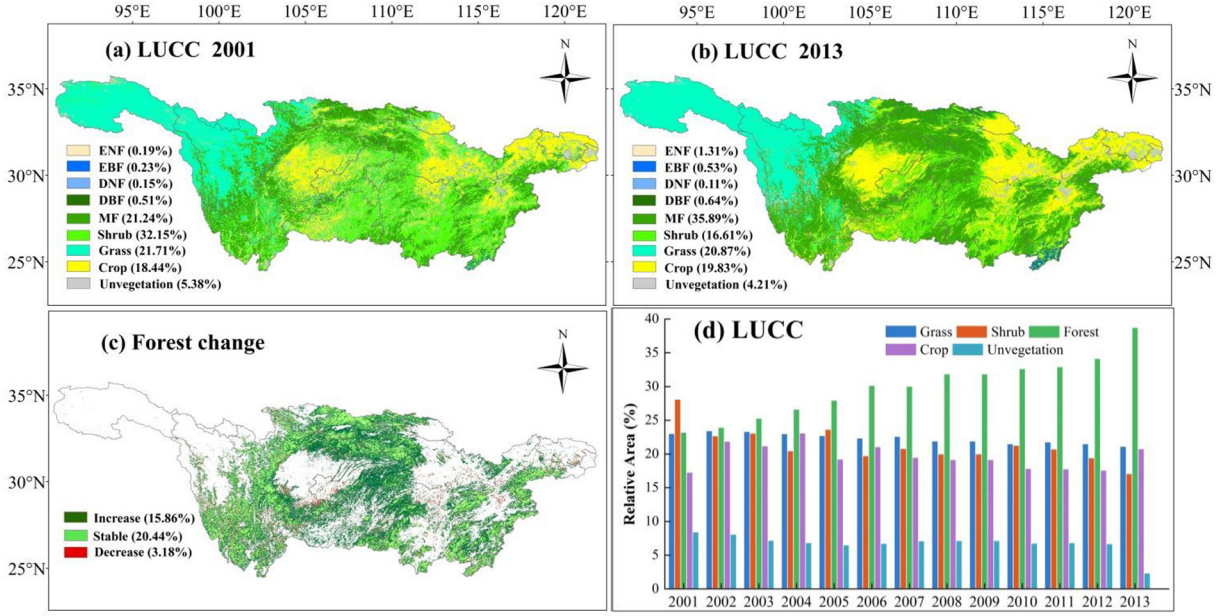

Fig. 9. Land use and land cover change (LUCC) in the YRB. (a) LUCC in 2001, (b) LUCC in 2013, (c) forest changes from 2001 to 2013, and (d) percentage of major land use types in the YRB through time.

Table 1
The conversion of land use during 2001–2013 (unit: 10^2 km^2).

Land use types	Grassland	Urban land	Shrub	Forest	Farmland
Grassland	3137.42	5.97	271.02	352.44	307.65
Urban land	15.18	76.37	122.14	107.72	187.74
Shrub	313.43	12.58	1593.83	2263.58	777.31
Forest	89.91	1.18	242.21	3638.01	103.78
Farmland	52.72	29.84	515.31	268.67	2184.93
Variation	−397.33	-381.05	-2037.62	2733.94	796.37

reached 6.85×10^5 km^2 in 2013 and the forest cover rate increased from 23.12% in 2001 to 38.98% because of the afforestation projects, which achieved remarkable results. At the same time, there are prominent spatial differences in the effectiveness of afforestation project. 20.73% of the region was characterized by high project effectiveness, mainly in the northeastern parts of Sichuan Province and northern part of Hubei Province. Meanwhile, low project effectiveness was found in 4.7% of the YRB, mainly concentrated in the Hengduan mountainous areas of southwestern Sichuan province. In these areas, the ecological environment has been improved due to the implementation of the ecological restoration project. However, dry-hot plateau mountain valleys, with high elevation, thin soil layer, scarce of water, increasing the difficulties of afforestation, combined with the long period of forest growth, the effectiveness of ecological engineering are not obvious at present (Tong et al., 2017; Chen et al., 2010; Miao et al., 2010).

4.5. The relationship between population density and changes in the GSN

4.5.1. Population size and changes

The total population in YRB increased from 5.36×10^8 in 1995 to 5.88×10^8 in 2010 according to the Chinese census database. Due to the constraints of natural geography and economic development, the distribution of population showed great spatial differences, relatively concentrating in the Sichuan Basin, central part of Anhui province and the eastern coastal areas (Fig. 11a). We calculated population changes between 1995 and 2010 using two raster maps (Fig. 11b). The regions where the population distribution decreased between 1995 and 2010 were mainly in the Hunan and Hubei province as well as in the western portion of the Jiangsu province. Owing to the rapid urbanization and economic development in the central cities of the country, a large population migrating from the central region such as Hunan, Hubei and southern Zhejiang into economically developed areas.

4.5.2. The relationship between population density and vegetation trends

In order to analyze the effect of population density on vegetation coverage, we divided the average population density into six groups which named G1, G2, G3, G4, G5 and G6. Meanwhile, we calculated population density changes between 1995 and 2010 and separated the magnitude of population density change into six groups, which named BH1, BH2, BH3, BH4, BH5 and BH6 (Table 2). The average trends for annual GSN and residual GSN in each group of population density were compared. The annual GSN trends for all groups were > 0 according to the average population density, except in the sixth group when the average population distribution at the range of > 1500 people/km^2, and the annual GSN trends peaked when the average population was within a 500–800 people/km^2 range (Fig. 12a). Residual GSN trends displayed the characteristics of inverted U curve and it peaks within the range of 500–800 people/km^2 as well. This showed that people tended to live in areas with good vegetation conditions, and a certain population could maintain the stability of vegetation growth, but the dense population had a damaging effect on vegetation. According to the changes of population density, the trends in annual GSN increased from the first group to the fifth group, and the average residual GSN trends achieved the maximum value in the fifth group when the population density reduced by 200–500 people/km^2 (Fig. 12b). This suggested that forest has turned green in most region, and in the areas with higher loss or migration of population, the greening rate is larger. To some extent, the massive emigration of the population alleviated the pressure of the ecosystem and promoted the improvement of vegetation condition in the ecologically fragile areas (Cao et al., 2006; Gesest et al., 2010; Jia et al., 2014).

Based on the spearman correlation analysis, the average population density was negatively correlated with annual GSN ($r = -0.61$), and the changes of population density was positively correlated with annual GSN ($r = 0.43$), but both of them were not significantly correlated with the GSN. The main interference factor was that, in addition to economic development, the attractiveness of eco-environment to human migration was increasing, and people tended to move to areas with good vegetation status. At the same time, large-scale population migration

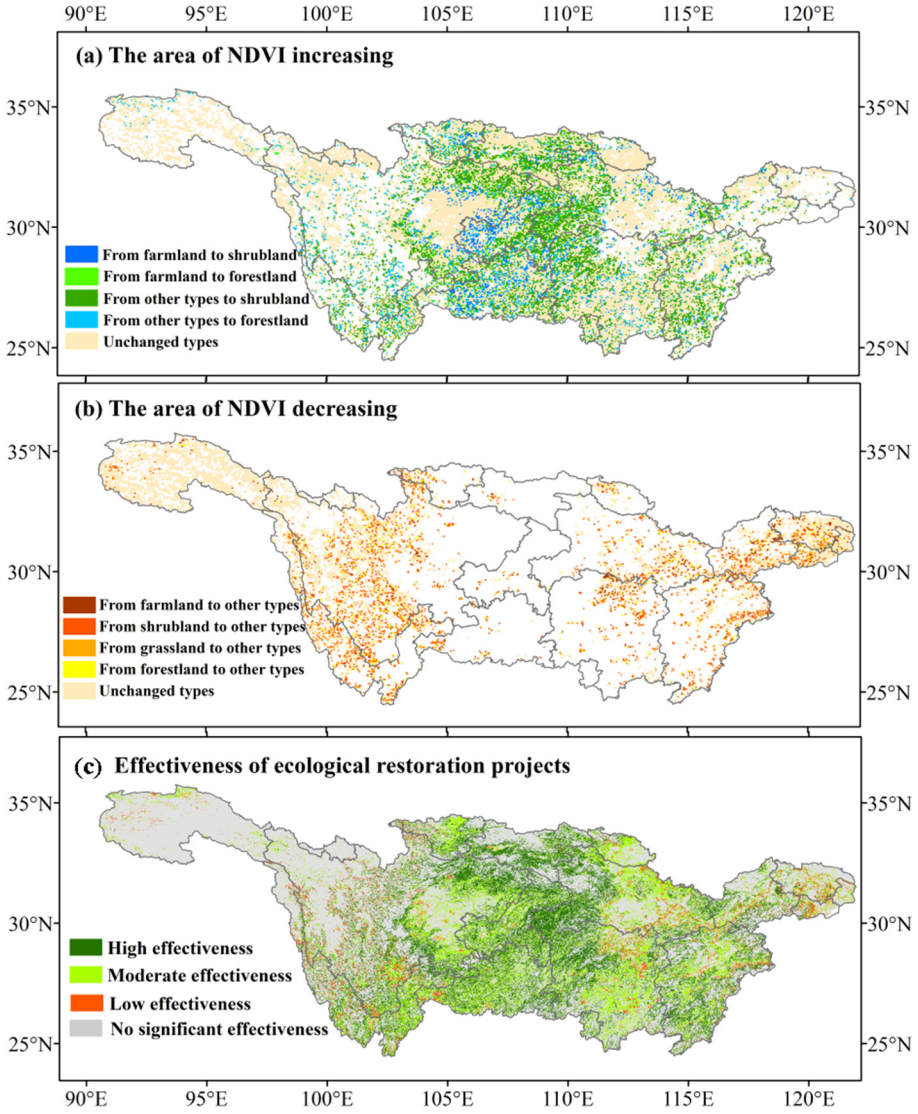

Fig. 10. Spatial distribution of LUCC transitions for different NDVI trends: (a) increasing area of NDVI, (b) decreasing area of NDVI, (c) Spatial distribution of ecological Engineering effectiveness levels of at pixel level.

was mainly due to the fact that the original ecological environment had been severely damaged or land cover had been changed after the migration (such as migrants from Three Gorges reservoir), characterized by the degradation of vegetation (Yang, 2008). Meanwhile, the average population density was positively related to the residual GSN, with the correlation coefficient of 0.134 ($p < 0.001$). Compared with the average population density, the correlation between residual GSN trends and the changes of population density was no significant, and the correlation coefficient was −0.004.

5. Discussion

5.1. Trends of vegetation changes and response to climatic factors

Our findings demonstrate that vegetation conditions in most areas of YRB have improved in the past 30 years, which are consistent with previous research (Deng et al., 2014; Miao et al., 2010). By analyzing the GSN values of the two periods before and after the turning point, we found that the GSN value in the conservation period (1995–2015) was

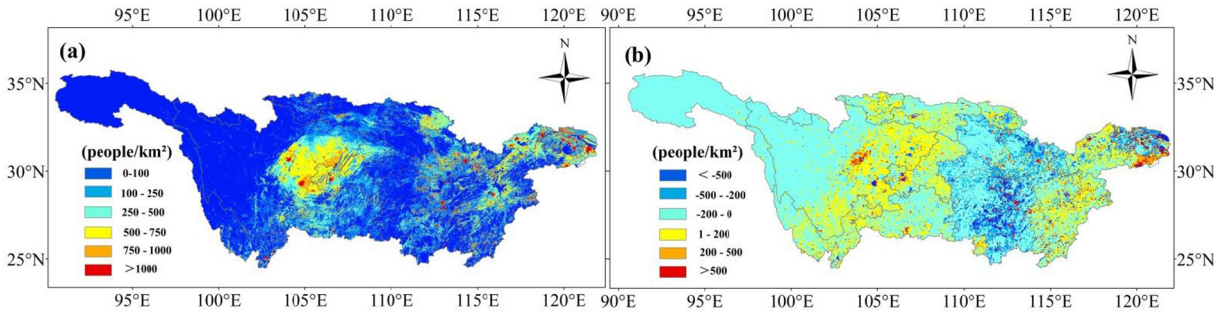

Fig. 11. Spatial distribution of the average population density (a) and the changes of population density in YRB from 1995 to 2010.

Table 2
Grouping of average and variation values of population density.

Group	Average population density (people/km^2)	Group	Population density change magnitude (people/km^2)
G1	0–100	BH1	< −500
G2	100–250	BH2	−500 to −200
G3	250–500	BH3	−200 to 0
G4	500–750	BH4	1–200
G5	750–1000	BH5	200–500
G6	> 1000	BH6	> 500

significantly higher than that in the reference period (1982–1994). Some studies attribute this apparent vegetation greening to the large percentage of croplands converting to forests (Zhu et al., 2016; Hua et al., 2017). However, there are other studies showing that both climatic factors and human activities have contributed to China's regional greening trends in recent decades. For instance, Piao et al. (2015) believes that rising atmospheric CO_2 concentration and nitrogen deposition have significant contributions to vegetation greenness. To separate and analyze the effects of climatic and anthropogenic factors on NDVI, we adopted a residual analysis method based on NDVI-climate model.

The response of vegetation coverage to temperature in YRB is stronger than that of precipitation, which is consistent with the results of other studies (Nan et al., 2010; BAI et al., 2012). Precipitation has a low impact on vegetation in YRB as a result of densely distributed rivers, while temperature has become the restricting factor of vegetation growth in most areas. We noted that there is no significant correlation between vegetation coverage change and climatic factors in some area, which is related to anthropogenic factors, especially the implementation of ecological engineering and population migration in recent years.

5.2. Linking human-induced vegetation trends to forest change

Quantitatively determining the effect of human factors on vegetation variations is crucial for optimizing subsequent management of vegetation ecosystem. Our research shows the impact of human activity on vegetation changes: positive impacts (central and northern regions), negative impacts (southwestern regions), and no significant impacts (Fig. 8). By comparing with the distribution of forest land changes in Fig. 9c, we can see strong consistency between the areas where anthropogenic factors have a positive impact on GSN and the areas with increased forest land in the central region of YRB. This showed that the land use change caused by afforestation is the main human factor to promote vegetation growth in the YRB. Liu et al. (2015) and Wang et al. (2015) confirmed this result and showed the significant correlation between cumulative afforestation area and NDVI. The area of forest reduction is mainly distributed on the south edge of Sichuan Basin, while negative impact of anthropogenic factors on vegetation is concentrated in the southwestern mountainous areas. One reason why this negative impact concentrated in these areas is that the vegetation species has changed during the past 10 years. Large-area deciduous broadleaf forests were replaced by artificially planted evergreen needleleaf forests (Fig. 9), whereas the NDVI values of needleleaf forests was smaller than that of broad-leaved forests (Hua et al., 2017). Furthermore, the effectiveness of afforestation in southwestern mountainous areas is relatively poor (Fig. 10), which also contributed to the downward trend of residual NDVI in southwest China (Tong et al., 2017).

5.3. Factors that affect the effectiveness of afforestation project

We identified the effectiveness of the implementation of ecological afforestation projects in YRB at the pixel scale based on a spatial superposition analysis. The different degree and spatial variability of the effectiveness of ecological restoration project could be explained by the interaction between climate, terrain and human management. The vast expanse of YRB led to a distinct climate difference. Over the past 30 years, temperature in source region of YRB has been increasing prominently, at the rate of 0.62 °C per decade, coupled with an almost negligible increase in precipitation of 20.5 mm per decade, resulting in a challenging condition for the survival of newly planted vegetation (Nan et al., 2010; Zhou et al., 2009). Additionally, frequent extreme weather events have become a serious hazard in recent years, which threaten the growth of vegetation (Liu et al., 2014a,b; Guan et al., 2015).

The differences of elevation and slope gradients also affected the effectiveness of ecological restoration projects. As presented in Fig. 12, the areas where forestland growth is relatively fast are mainly concentrated in the area below 1500 m above sea level. These areas are more susceptible to human activities, and the development of ecological engineering was more extensive and beneficial. Whereas areas above 1500 m above sea level are difficult of large-scale afforestation because of the sparsely populated. In the same way, with the increase of slope, the growth of forestland area gradually slowed down. Because of the fragile environment, the area with steep slope is more vulnerable to the negative effects of human-induced factors (indiscriminate deforestations); couple with high proportion of the original forestland, the growth of forestland is not obvious.

In addition to climate and topography, the human management plays an important role in the effectiveness of ecological restoration projects. Proper management system includes three aspects: appropriate tree species selection and planting scheme, the participation and compensation of the local residents and effective supervision of plantations. In the process of afforestation, the preference for exotic trees often ignores the actual natural conditions of the locality, which leads to the low survival rate of trees (Zhao et al., 2007; Duan et al., 2014). According to the data of the State Forestry Bureau, China has completed the task of returning farmland to forests 298,000 square kilometers in

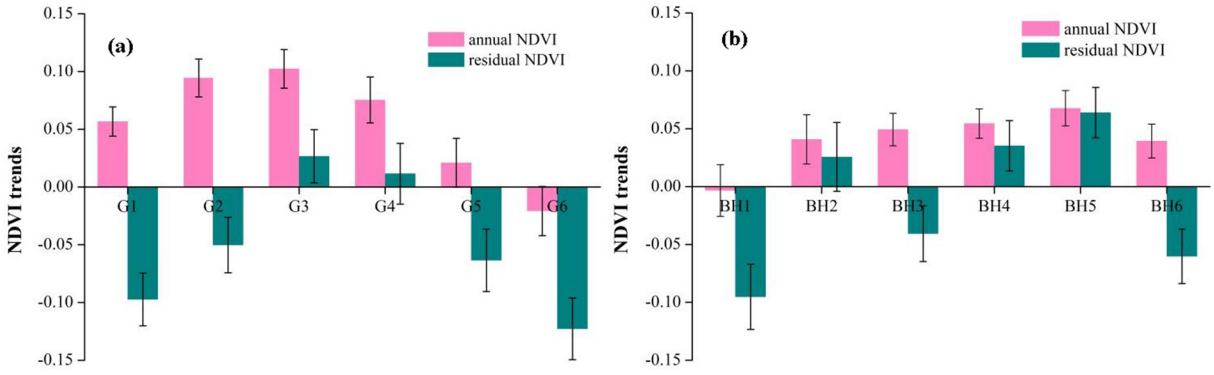

Fig. 12. Trends of the annual NDVI and residuals in different population density groups. (a) the average population density, and (b) the changes of population density .

2015, the forest coverage rate in the project area increased by an average of 3%, which has made remarkable achievements in the ecological recovery. However, it is noteworthy that the basic afforestation model at the present stage of the valley in YRB is still forced to plant trees by means of administrative measures, with a technical route of reverse natural succession from arbor to shrub to grassland (Huang et al., 2013). This planting scheme is contrary to the natural conditions of the barren soil and the lack of water resources in the southwest, resulting in low effectiveness of ecological engineering (Fig. 10c) (Tong et al., 2017; Liu et al., 2014a,b).

Interventions that tradeoff between ecological maintenance and economic development need to be tailored to different landscapes and scales (Raudsepp-Hearne and Mooney, 2010). Huang et al. (2013) reminded that environmental goals cannot be achieved without some type of economic development that could provide a livelihood for the people affected by the program. The program of "Grain to Green" and "Natural Forest Resources Protection" are important means to curb ecological degradation, but at the same time, "Returning Farmland" has left the peasants losing the basis for survival, "Natural forest Protection" has deprived local people of important employment opportunities and firewood resources (Song et al., 2015). Although the criteria and the duration of the subsidy were clarified, but the interests of the locals were not fully guaranteed, forcing peasants to return their forest or grass back into the cultivated land (Cao et al., 2009; Chen et al., 2009). Especially in areas with higher elevation (> 2000 m) and steeper slope (> 25°), the phenomenon of farmland reclamation is more outstanding (Fig. 13). Hence, Zhang et al. (2016) suggested that farmers should be provided with attractive enough subsidies, and through the incentive policy to promote farmers to take the initiative to participate in ecological construction. Some areas of the engineering are in regions far from the city center with sparse population and limited access (e.g. southwestern part of Sichuan province), which makes it difficult for the government to monitor the efficiency of ecological engineering. This is consistent with reports of unsuccessful tree or grass growth in these areas (Zhou et al., 2009; Chen et al., 2010; Huixia et al., 2011). Even if success is not uniform, many regions showed a positive human-induced trend due to the impact of ecological engineering. This indicated that if properly implemented, ecological restoration projects could greatly benefit China in improving ecological problems. It is noteworthy that the problems of ecological restoration projects are gradually highlighted, and special attention needs to be paid in later studies.

5.4. The impact of population migration on vegetation trends

Regional population change is affected by both natural change (birth rate and mortality rate) and mechanical change (population migration) of the initial population (Guo-Ping and Chen, 2009). Many studies have shown that except for the Qinghai-Tibet Plateau, the population density changes in China are mainly related to population migration (Zou, 2011). Since the mid-1990s, the growing urbanization process has resulted in large-scale population movements within YRB, and the traditional way in which rural residents have made a living has changed. Population migration changes the size and structure of the initial population and also affects regional land use and vegetation changes (Olsson et al., 2005; Gesest et al., 2010). The large-scale migration of the working-age population in YRB has promoted the restoration of vegetation from the following aspects: The emigration of the population created a large number of non-farm jobs, pulling farmers out of the land, which contribute to reducing dependence on traditional crops and animal husbandry, facilitating the abandonment of sloping cultivated land, and decreasing the likelihood of reclamation (Yang, 2008). Additionally, with the rising opportunity cost of farming, some farmers abandoned their cultivation, resulting in the gradual idleness and desolation of arable land, numerous cultivated land degraded into woodland and grassland (Shao et al., 2015). Furthermore, the improvement of rural living standards has promoted the transformation of the rural household energy consumption structure, which has led to the shift of traditional fuelwood to cleaner, more efficient and environment-friendly energy (Cai et al., 2014).

In addition, uncertainties in attributing the observed vegetation changes cannot be ignored. The NDVI data used in this study was from the GIMMS 3 g datasets with the coarse spatial resolution of 8 km, whereas land use data was derived from the MODIS land cover product (MCD12Q1 v51) with a spatial resolution of 250 m. Although these data have the same spatial reference through re-projection processing, perfect consistency is difficult to guarantee (Cai et al., 2014). This problem is also unavoidable in a combination of data from different sources. Moreover, time interval for population data based on three national censuses is from 1995 to 2010, lacking of population data for the last 5 years, which may weaken the reliability of assessing the specific impact of population factors on vegetation changes. Uncertainties also arise from the drawbacks of regression approach. Vegetation coverage change is a complex process of multi-cyclical interaction (Xu et al., 2014; Zhang et al., 2016). However, due to the inability of the regression approach to characterize the non-linear relations between NDVI and different environmental factors, the influence of individual variables cannot be completely isolated, which affects the robustness of attribution analysis results to some extent (Cantrell, 2008; Frazier, 2014; Wrigley, 1978). Finally, other factors affecting vegetation change, i.e., radiation, CO_2 fertilization and water stress, should also be taken into consideration. To do so, applying a comprehensive model that can quantify most of the relevant factors is needed in the future

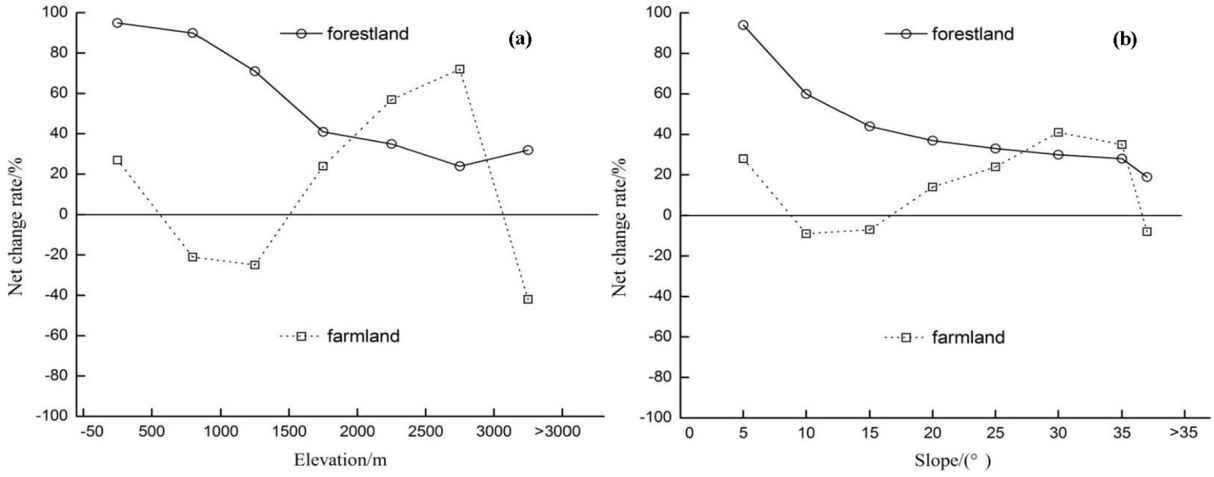

Fig. 13. Net change rates of forest and farmland along elevation (a) and slope (b) gradients from 2001 to 2013.

(Piao et al., 2015; Zhu et al., 2016).

6. Conclusion

This study analyzed the temporal and spatial changes of vegetation coverage over the YRB from 1982 to 2015 and distinguished the impacts between climate change and human-induced factors (mainly ecological restoration projects and demographic changes) on vegetation dynamics. A residual analysis method based on NDVI-climate model was adopted to quantify the effects of anthropogenic factors on vegetation trends. These human-induced vegetation trends were found to be closely related to afforestation projects. Following conclusions could be drawn based on the above analysis:

(1). Vegetation trends experienced an overall downward trend from 1982 to 1994, after which there was a marked upward trend in most area of YRB between 1995 and 2015, and the highest growth rate was observed in Chongqing (greater than 0.04 GSN $year^{-1}$).
(2). NDVI-climatic correlation analysis demonstrated that annual temperature significantly restrict vegetation growth about 34.1% of the total area as the limiting factor, whereas precipitation significantly limits growth accounted for only 1.4% of YRB.
(3). Vegetation improvement caused by human activities accounted for 6.32%, whereas 16.9% of the area appeared vegetation degradation due to the impact of human factors. Human activities in the southern and Sichuan basin areas of Shaanxi Province have more positive impacts on vegetation, while the effects of human activities on vegetation in the northern and Shanghai areas of Yunnan are predominantly negative.
(4). As a result of the implementation of the ecological restoration project, the forest land increased by 2.73×10^5 km^2, accounting for 15.36% of the basin area between 2001 and 2013. In total, 36.32% of the total area had a positive effectiveness among which 20.73% of the regional ecological restoration work had achieved remarkable results. 4.71% of the region was less effective. No significant effectiveness was detected in the remaining areas (74.56%).
(5). Areas with increased forest land area (mainly in the central region) have a strong spatial consistency with the areas where human activities have positive impacts on vegetation. Although the area of forest land in southwestern China increased, the residual GSN showed a decreasing trend due to the poor effectiveness of afforestation projects.
(6). In areas with low eco-engineering effectiveness, in addition to harsh climatic conditions and rugged terrain, man-made management such as inappropriate tree species selection, imperfect supervision of the department, low compensation rate of farmers, also greatly affected the restoration and growth of vegetation.
(7). Population mobility and migration also made a contribution to ecological restoration. The emigration of a large number of labors promoted the restoration of vegetation by facilitating abandonment of sloping cultivated land, and reducing the negative disturbance to forestland.
(8). Using more detailed population migration data will help to further explore the spatial variation of the contributions. In future studies, we will focus on the mechanism of out-migration-environmental action.

Acknowledgements

This work was financially supported by National Natural Science Foundation of China (No.41601044), the Special Fund for Basic Scientific Research of Central Colleges, China University of Geosciences, Wuhan (No.CUG150631, CUGL170401). We would like to thank China Meteorological Administration (CMA) for providing the meteorological data.

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